Parallel Simulation of Electron Cooling Physics for Relativistic Ion Beams

D.L. Bruhwiler,[1] G.I. Bell,[1] A.V. Sobol,[1]
P. Messmer,[1] P. Stoltz,[1] J.R. Cary,[1,5]
V. Litvinenko,[2] E. Pozdeyev,[2]
A. Fedotov,[2] I. Ben-Zvi,[2]
R. Li,[3] Y. Zhang,[3] S. Derbenev,[3]
J. Qiang,[4] R. Ryne[4]

1. Tech-X Corporation
2. Brookhaven National Lab
3. Thomas Jefferson National Lab
4. Lawrence Berkeley National Lab
5. University of Colorado

ComPASS Collaboration Meeting
UCLA, Dec 2, 2008

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Outline

- **Motivation and Overview**
  - future luminosity upgrades of RHIC at BNL
  - Long range: a new Electron-Ion Collider (EIC)
- **Previous Work**
  - "high-energy" electron cooling
- **Status of Recent Efforts**
  - concept of "coherent" electron cooling (CEC)
  - accurate treatment of the modulator section
- **Future Plans**
  - use δf PIC algorithm for modulator simulations
  - explore finite e- beam size, other complications

Physics Motivation for Cooling Ion Beams

Unanimous recommendation of the Quantum Chromodynamics Town Meeting, at Rutgers University, New Jersey, January, 2007

A high luminosity Electron Ion Collider (EIC) is the highest priority of the QCD community for new construction after the Jlab12 GeV and RHIC II upgrades. EIC will address compelling physics questions essential for understanding the fundamental structure of matter:

- *Precision imaging of the sea-quark and gluons to determine the spin, flavor and spatial structure of the nucleon*
- *Definitive study of the universal nature of strong gluon fields in nuclei*

The collider and the detector designs must be developed expeditiously.

C. Aidala *et al*. (The EIC Working Group), "A High Luminosity, High Energy Electron-Ion-Collider; *A New Experimental Quest to Study the Glue that Binds Us All,"* White Paper prepared for the NSAC LRP (2007).
http://www.phenix.bnl.gov/WWW/publish/abhay/Home_of_EIC/NSAC2007/070424_EIC.pdf

ERL-based Layout for eRHIC

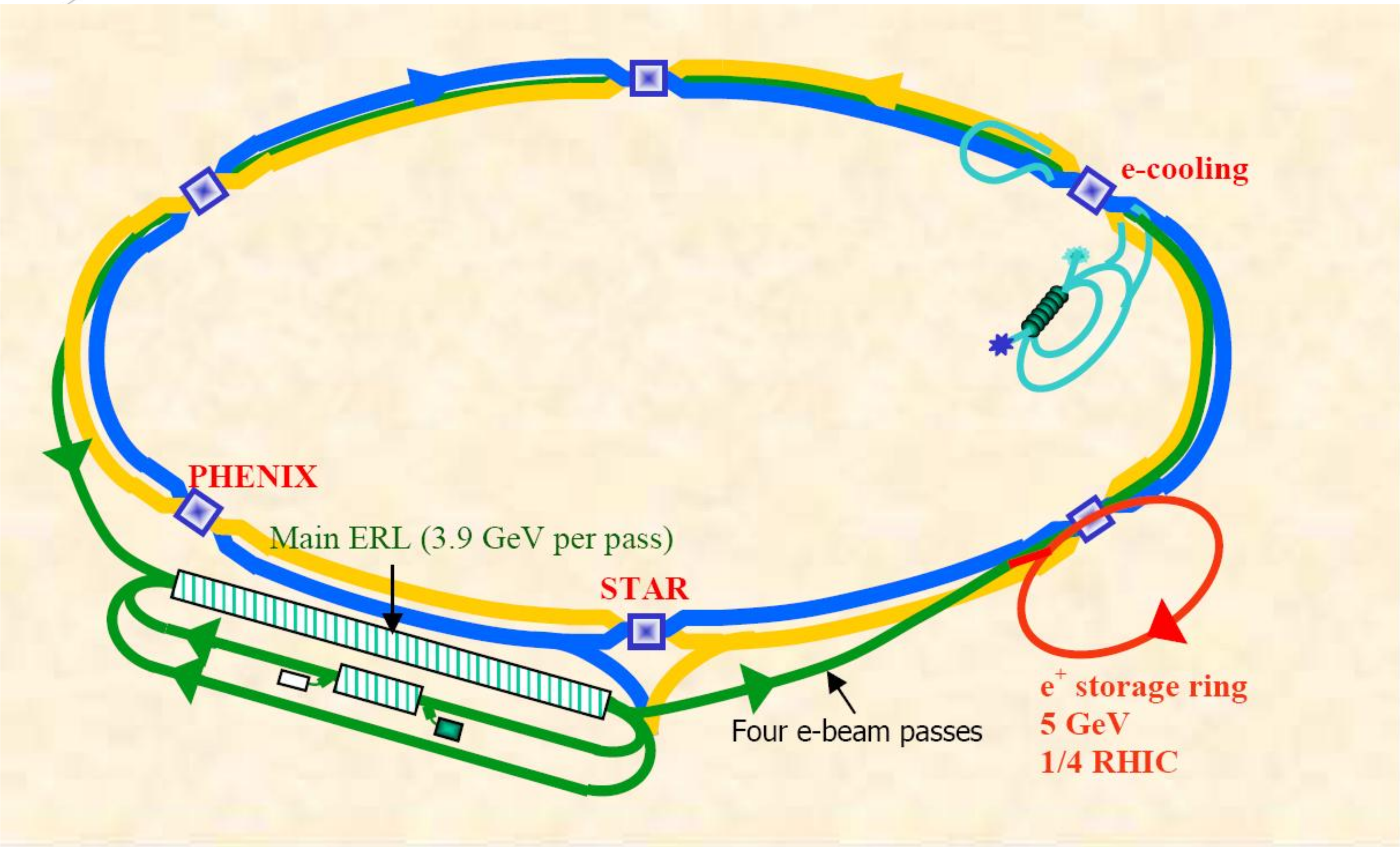
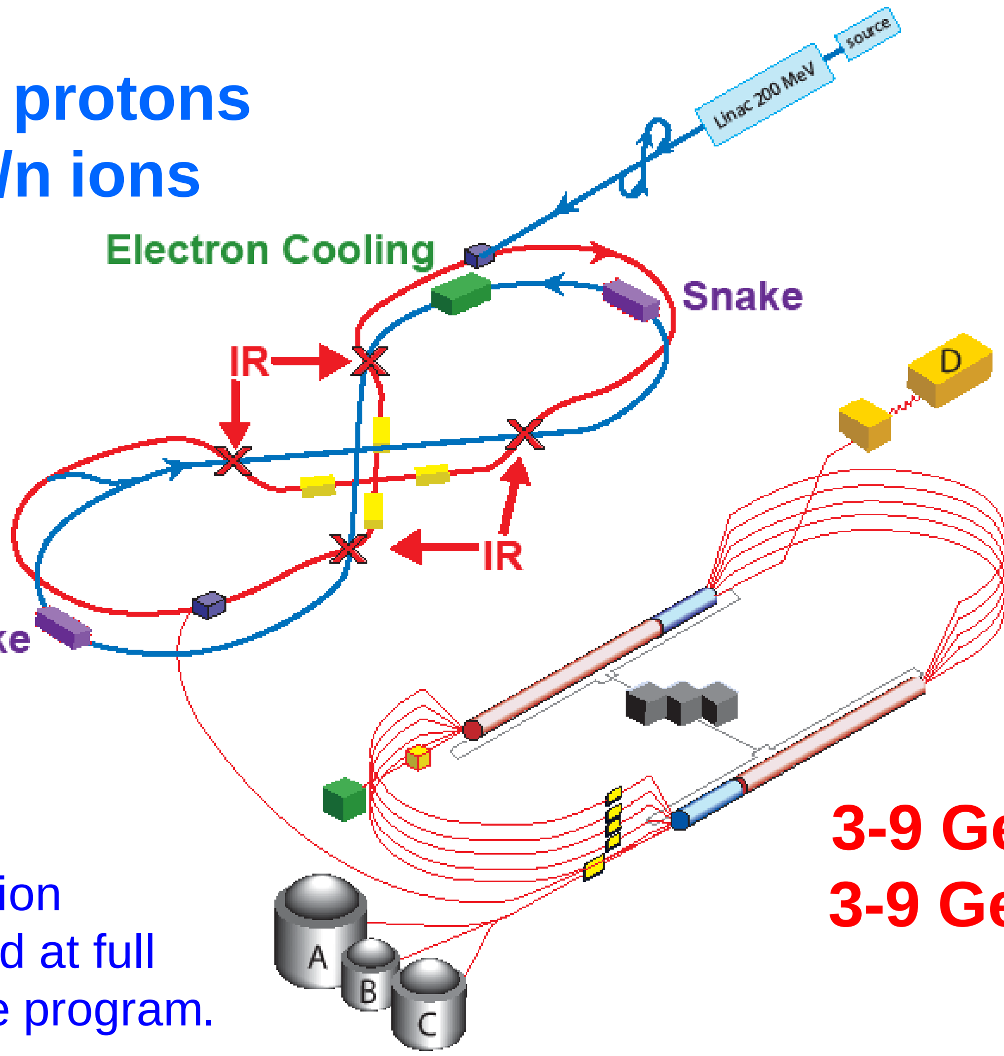


Image taken from 2007 eRHIC position paper
http://www.agsrhichome.bnl.gov/eRHIC/AD_Position_Paper_2007.pdf

ELIC Schematic
(Electron – Light Ion Collider)

30-225 GeV protons
15-100 GeV/n ions



3-9 GeV electrons
3-9 GeV positrons

Green-field design of ion complex directly aimed at full exploitation of science program.

Previous work: Simulation of conventional "high-energy" electron cooling for RHIC-2

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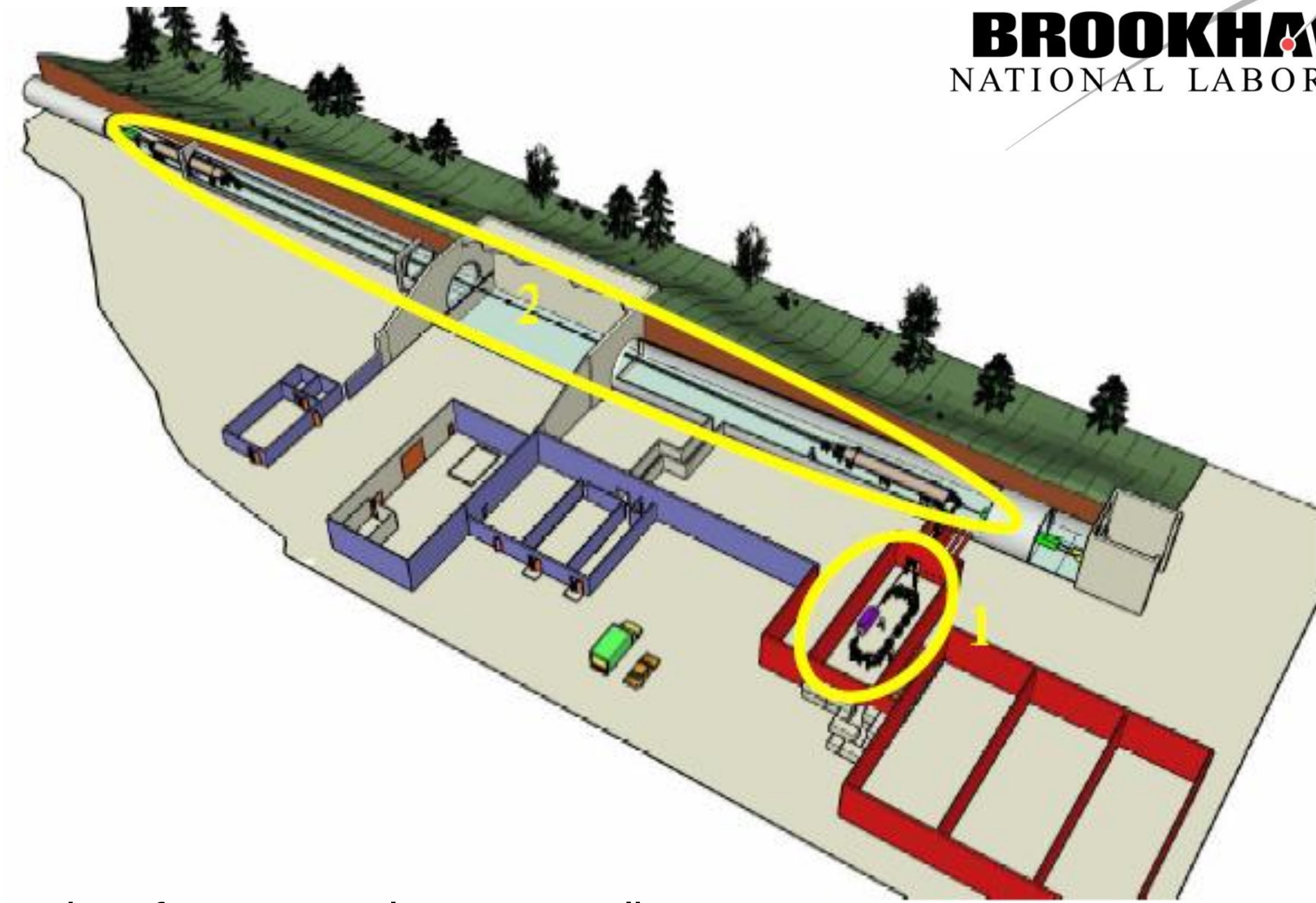

Image taken from BNL Electron Cooling Group:
http://www.bnl.gov/cad/ecooling/HighEnergyEcooling.asp

VORPAL simulations accurately calculate friction force on relativistic Au^{+79} ions to support electron cooling designs

- **Culmination of years of work, beginning in 2002**

A.V. Fedotov, D.L. Bruhwiler, A. Sidorin, D. Abell, I. Ben-Zvi, R. Busby, J.R. Cary, and V.N. Litvinenko, "Numerical study of the magnetized friction force," Phys. Rev. ST Accel. Beams **9**, 074401 (2006).

A.V. Fedotov, I. Ben-Zvi, D.L. Bruhwiler, V.N. Litvinenko and A.O. Sidorin, "High-energy electron cooling in a collider," New J. Phys. **8** (2006), p. 283.

G.I. Bell, D.L. Bruhwiler, A. Fedotov, A.V. Sobol, R. Busby, P. Stoltz, D.T. Abell, P. Messmer, I. Ben-Zvi and V.N. Litvinenko, "Simulating the dynamical friction force on ions due to a briefly co-propagating electron beam", J. Comp. Phys. **227** (2008), p. 8714.

- **Conventional wiggler could replace expensive solenoid**
  - e- "wiggle" motion suppresses recombination with ~10 Gauss
  - provides focusing
  - reduces many technical risks
  - friction force should be reduced only by $\rho_{min} \rightarrow \rho_w$ in Coulomb log
    - suggested independently by V. Litvinenko and Ya. Derbenev
      - confirmed by detailed VORPAL simulations

$$\rho_w = \frac{\Omega_{gyro}}{k_w^2 v_{beam}} \sim 1.4x10^{-3} \lambda_w^2[m] B_w[G] / \gamma$$

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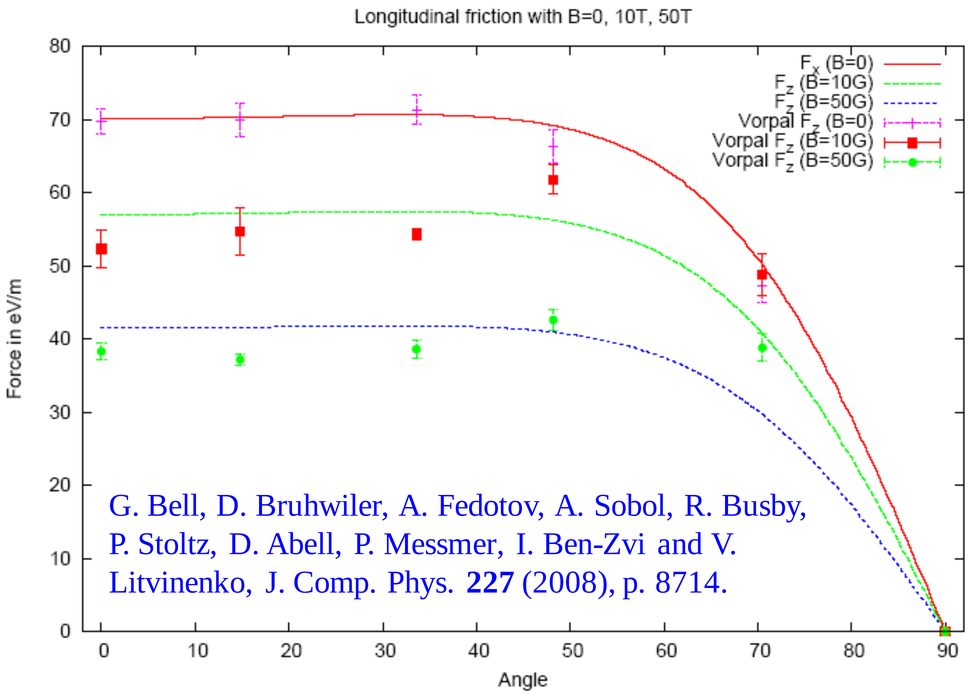
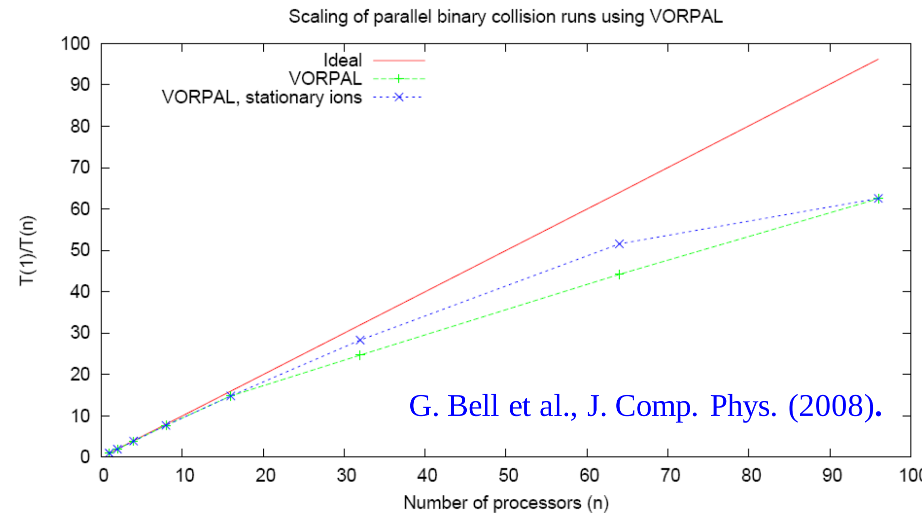
VORPAL

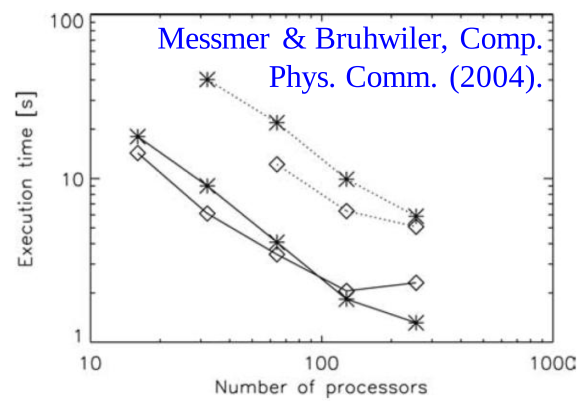
VORPAL simulations show logarithmic decrease of friction force in wiggler-based e- cooler for RHIC



For anticipated parameters of a RHIC e- cooler, friction force on a single Au^{+79} ion is shown as a function of the angle between the ion velocity vector and the beam axis; a modest decrease in the friction is seen, in agreement with theoretical estimates, as the wiggler field increases from 0 to 10 and 50 Gauss.



VORPAL molecular dynamics (MD) simulations of Coulomb collisions scale up to 96 proc's with 60% efficiency. A hybrid PIC/MD approach might do better.



Trilinos Poisson solve for 1026×65×65 mesh (solid) & 4104×65×65 mesh (dotted), using AMG preconditioner (diamonds) vs Gauss-Seidel preconditioner (stars) for CGS.

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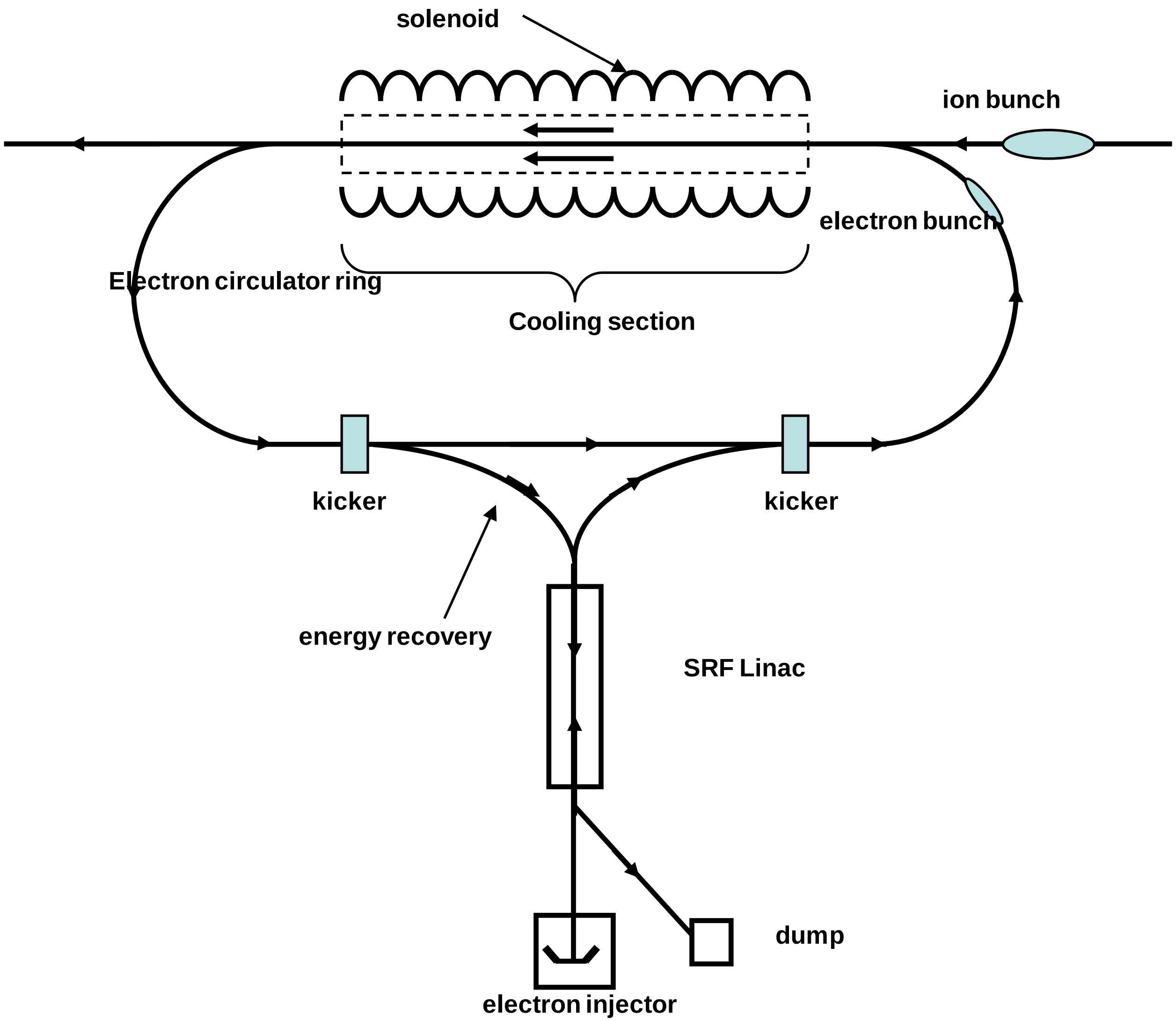
Schematic of Solenoid-Based Electron Cooler for ELIC



Self-Consistent Langevin Solution of the Fokker-Planck/Landau Equation

$$\frac{\partial f}{\partial t} + \mathbf{v} \cdot \frac{\partial f}{\partial \mathbf{r}} + \frac{\mathbf{F}}{m} \cdot \frac{\partial f}{\partial \mathbf{v}} = -\frac{\partial}{\partial \mathbf{v}} \cdot \mathbf{F_d} f + \frac{1}{2} \frac{\partial^2}{\partial \mathbf{v} \partial \mathbf{v}} : \mathbf{D} f$$

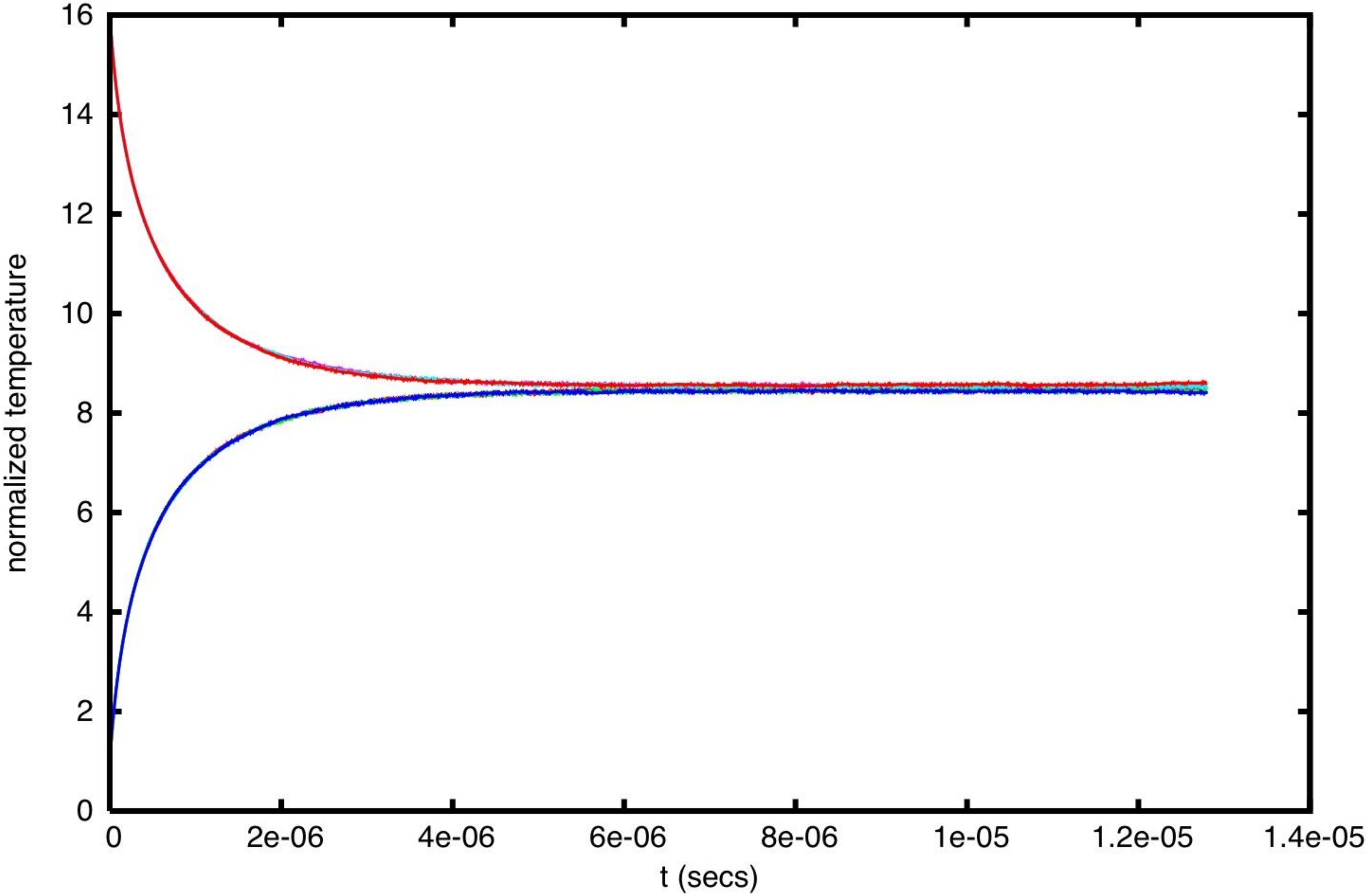
$$\mathbf{r}' = \mathbf{v},$$

$$\mathbf{v}' = \frac{\mathbf{F}}{m} + \mathbf{F_d} + \mathbf{Q} \cdot \mathbf{\Gamma}(t),$$

$$\langle \Gamma_i(t) \rangle = 0,$$

$$\langle \Gamma_i(t) \Gamma_j(t') \rangle = \delta_{ij} \delta(t - t').$$

A Test Example Showing Temperature Exchange in a 2-Species System



Motivation for CEC concept

- **Coherent Electron Cooling concept**
  - uses FEL to combine electron & stochastic cooling concepts
    Litvinenko *et al.*, FEL Conf. Proc. (2007); Litvinenko *et al.*, FEL Conf. Proc. (2008).
  - a CEC system has three major subsystems
    - **modulator**: the ions imprint a “density bump” on e- distribution
    - **amplifier**: FEL interaction amplifes density bump by orders of magnitude
    - **kicker**: the amplified & phase-shifted e- charge distribution is used to correct the velocity offset of the ions
  - standard electron cooling could work well for RHIC II…
  - but CEC could be orders of magnitude better:
    - stronger interaction implies shorter cooling times
    - effectiveness does not scale strongly with ion beam energy
      - could even be relevant to the LHC
  - modulator is now being simulated with VORPAL
    Bell *et al.*, “VORPAL simulations relevant to Coherent Electron Cooling,” EPAC Proc. (2008).

BNL has organized a Coherent Electron Cooling Collaboration

Vladimir N. Litvinenko, Ilan Ben Zvi, Michael Blaskiewicz, Yue Hao, Dmitry Kayran, Eduard Pozdeyev & Gang Wang
Brookhaven National Laboratory, Upton, NY 11973, USA

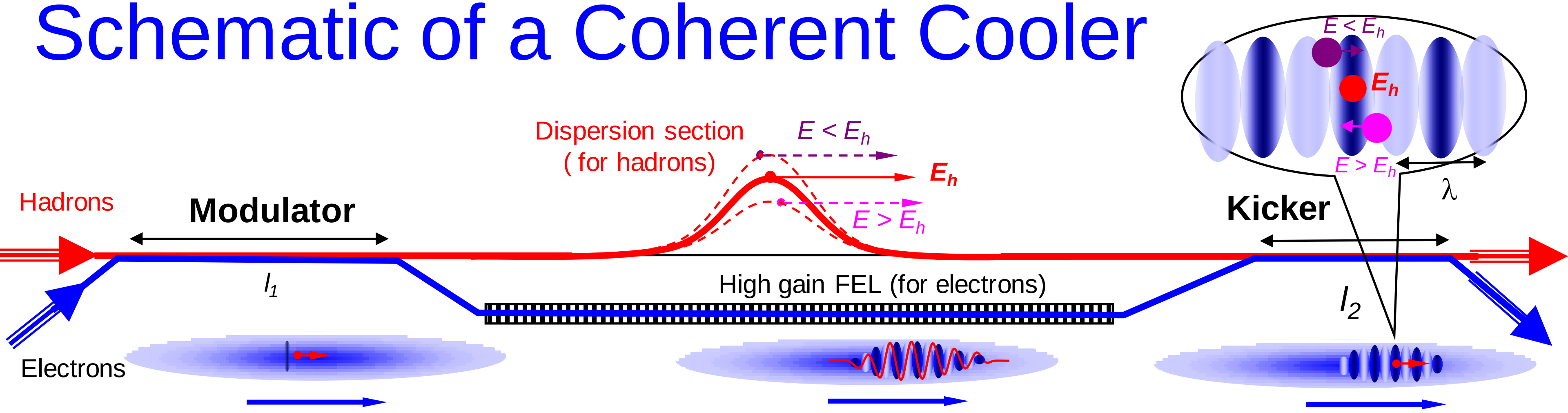
Oleg A. Shevchenko, Nikolay A. Vinokurov
Budker Institute of Nuclear Physics, Novosibirsk, Russia

George I. Bell, David L. Bruhwiler, Andrey Sobol
Tech-X Corp., Boulder, CO 80303, USA

Yaroslav S. Derbenev, TJNAF, Newport News, VA, USA

Sven Reiche, *UCLA, Los Angeles, CA, USA* ***(now at PSI in Switzerland)***

Schematic of a Coherent Cooler



Images courtesy of **V.N. Litvinenko *et al.*, FEL Conf. Proc. (2008).**

- **Modulator simulations must be very high fidelity**
  - suppress shot noise (correctly handled by FEL models)
- **Completely different from previous e- cooling simulations**
  - previously, dynamical friction force was the key metric
  - now, the electron density and velocity wake is what matters
- **New algorithms are being used**
  - previously, careful treatment of close binary collisions
  - now, electrostatic PIC with noise reduction
  - near future, δ-f PIC for higher fidelity

4 relevant dimensionless parameters

- **Infinite e- beam size**
  - only 4 dimensionless parameters
  - finite beam size will be simulated in the future

Parameter	Definition	Description
R	$R \equiv \sigma_{vx} / \sigma_{vz} = 3$	Ratio of transverse to longitudinal RMS velocity spread.
T	$T \equiv v_{ix} / \sigma_{vz}$	Ratio of transverse ion velocity to RMS velocity spread.
Z	$Z \equiv v_{iz} / \sigma_{vz}$	Ratio of longitudinal ion velocity to RMS velocity spread.
ζ	$\zeta \equiv Z_{ion} / (4 \pi n_e R^2 \lambda^3_D)$	Plasma nonlinearity parameter.
	$\zeta = 0.1$ in the following simulations	

- **VORPAL uses MKS**
  - use parameters relevant to Au^{+79} at RHIC

Parameter	Value	Definition
n_e	1.60×10^{16} e-/m^3	Electron Density
$\omega_p = (2\pi)8.98\, n_e^{1/2}$	7.14×10^9 radians/second	Plasma frequency in radians per second
$f_p = 8.98\, n_e^{1/2}$	1.14×10^9 cycles/second	Plasma frequency in cycles per second
$1/f_p$	0.88 nanoseconds	Plasma frequency time scale
$\lambda_D = \sigma_{vz}/\omega_p$	1.26 microns	Nominal longitudinal Debye radius
$(\sigma_{vx}, \sigma_{vy}, \sigma_{vz})$	$(27, 27, 9) \times 10^3$ m/sec	RMS electron velocity spread

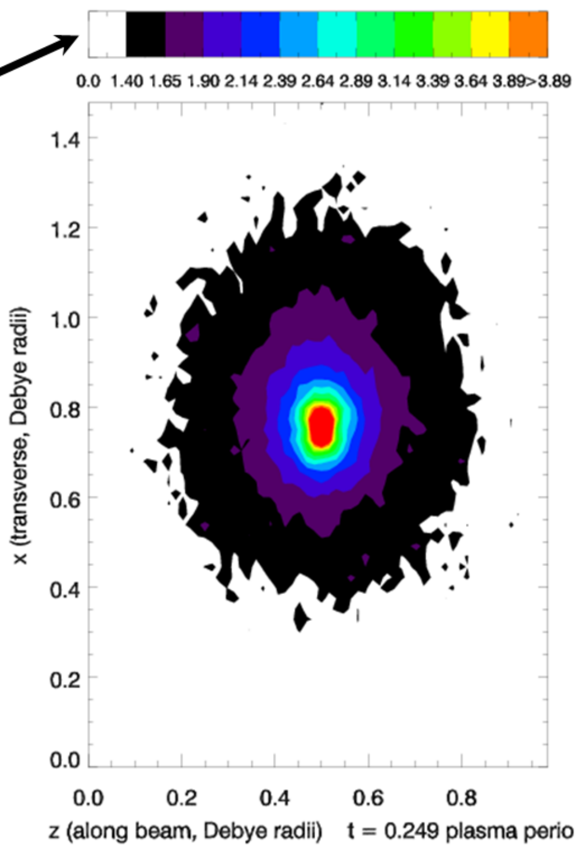
Temperature anisotropy distorts the wake

Stationary ion

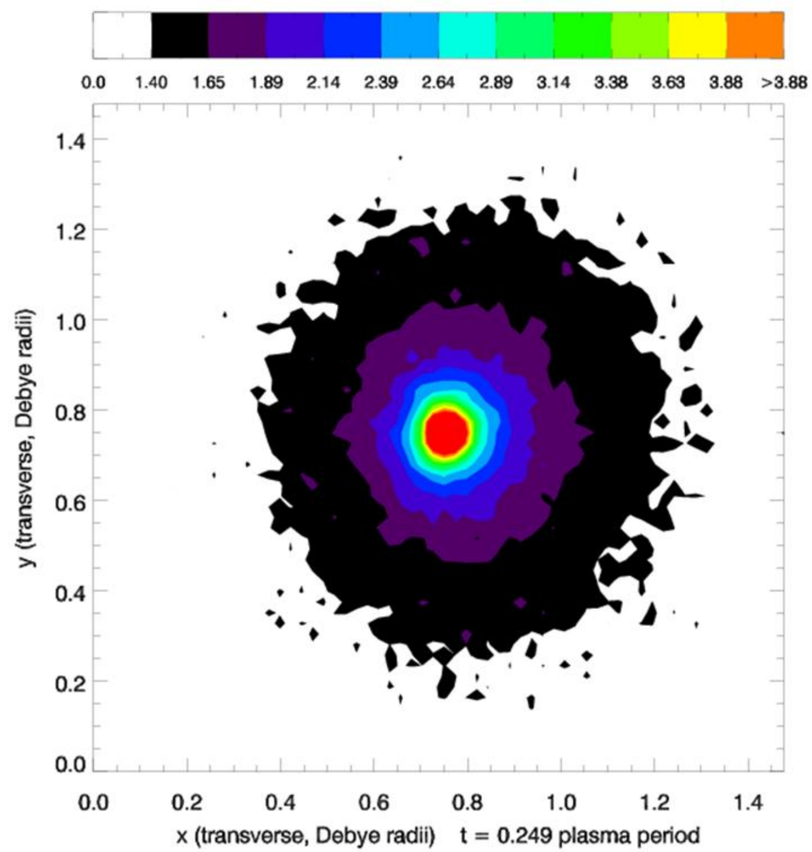
R = 3 (non-isotropic); T = 0 ; Z = 0

Z (along beam) vs. X (transverse)

density enhancement color scale



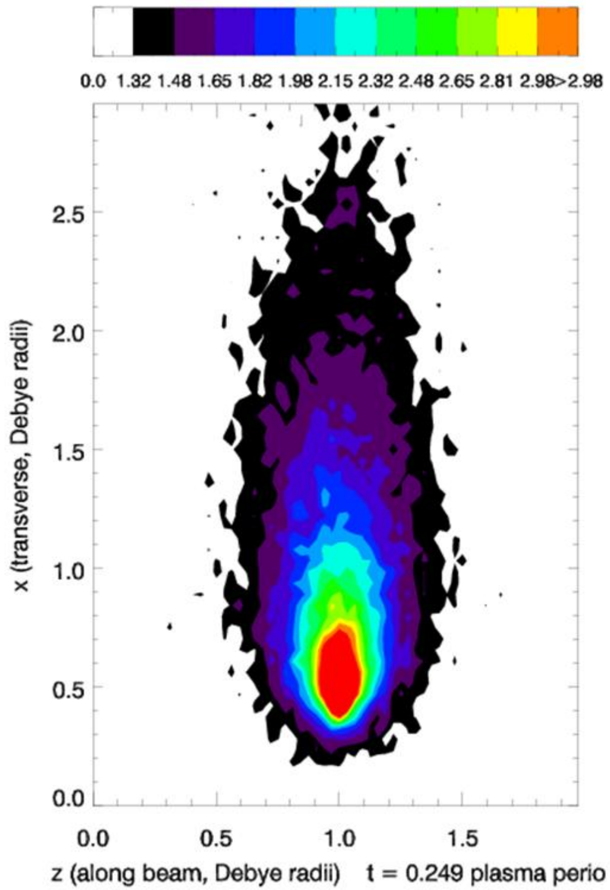
X (transverse) vs. Y (transverse)



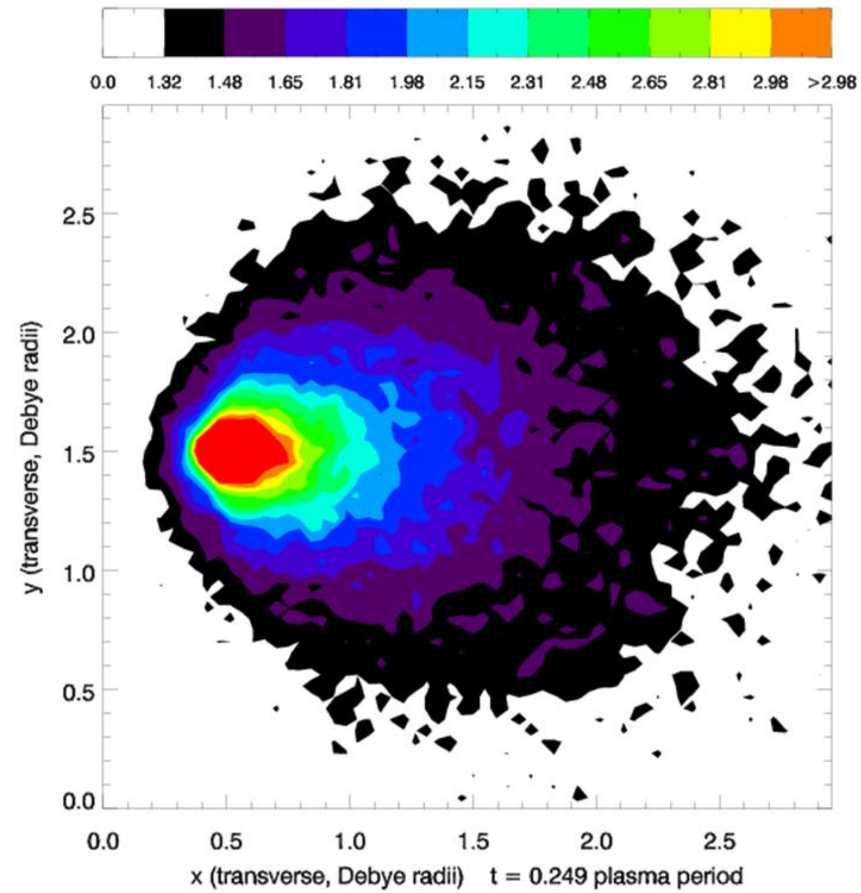
Ion velocity also distorts the wake

Ion moving transversely
R = 3; T = 5.6 ; Z = 0

Z (along beam) vs. X (transverse)



X (transverse) vs. Y (transverse)



Comparison with theory

- **New analytical results for e- density wake**

  G. Wang and M. Blaskiewicz, Phys Rev E ***78****, 026413 (2008).*

$$\tilde{n}(\vec{\mathrm{r}},\mathrm{t}) = \frac{Z n_o \omega_p^3}{\pi^2 \sigma_{\mathrm{v}x}\sigma_{\mathrm{v}y}\sigma_{\mathrm{v}z}} \int_0^{\omega_p t} \tau \sin\tau \left(\tau^2 + \left(\frac{\mathrm{x} - \mathrm{v_{hx}}\tau/\omega_p}{r_{Dx}} \right)^2 + \left(\frac{\mathrm{y} - \mathrm{v_{hy}}\tau/\omega_p}{r_{Dy}} \right)^2 + \left(\frac{\mathrm{z} - \mathrm{v_{hz}}\tau/\omega_p}{r_{Dz}} \right)^2 \right)^{-2} d\tau$$

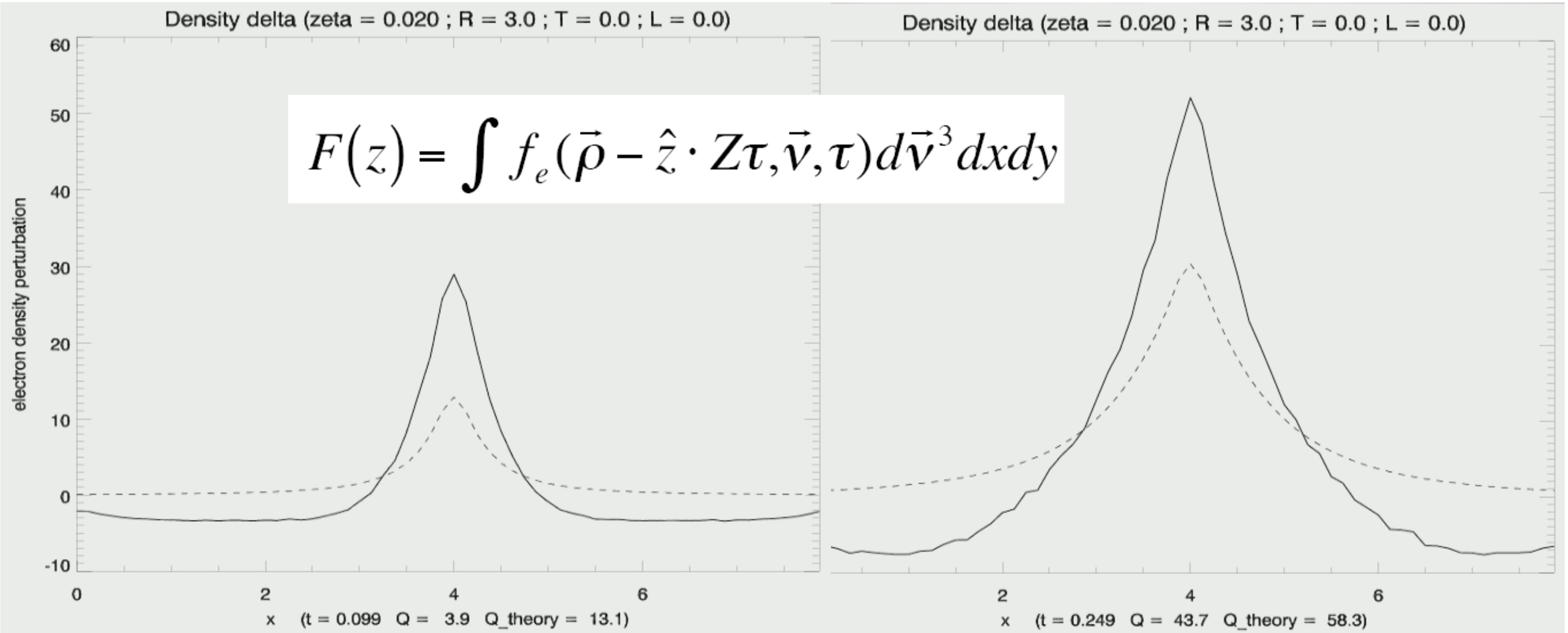
  – assumptions:
    - single ion; arbitrary velocities
    - uniform e- density; *anisotropic* temperature
      – "kappa=1" or Lorentzian velocity distribution
      – now implemented in VORPAL
      – for slow ions, results are very similar for Gaussian
    - linear plasma response; *fully 3D*

  – dynamics extends over many λ_D and $1/\omega_{pe}$

  – boundary conditions are important

Theory & numerics differ at early times

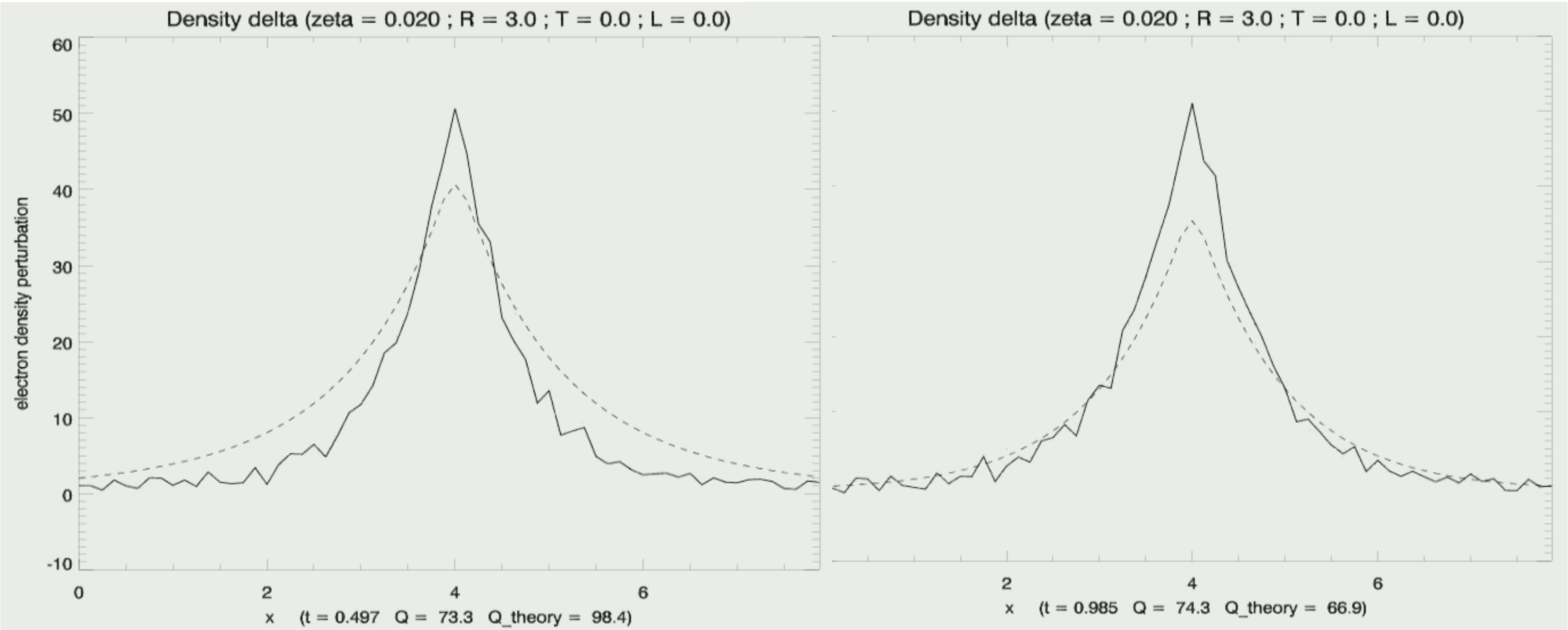
- **W&B assume infinite domain**
  - this e- reservoir moves inward at early times
  - VORPAL assumes external fields are zero



$$F(z) = \int f_e(\vec{\rho} - \hat{z} \cdot Z\tau, \vec{v}, \tau)\, d\vec{v}^3\, dx\, dy$$

Theory & numerics agree at later times

- **after t~$1/\omega_{pe}$, BCs become less important**
  – sufficiently close to ion, dynamics remains nonlinear
    - possibly exaggerated by cell size in simulations



Future plans – explore benefit of δf PIC

- **Non-ideal modulator simulations (no theory)**
  - consider effects of finite e- beam size
    - density gradients, vacuum interfaces, bulk space charge
    - distorted wakes; reflections from vacuum interface
    - no theory with which to compare
      - can't trust basic ES PIC → need algorithm for benchmarking
  - consider multiple ions (nonlinearities important?)
- **Implement δf PIC in VORPAL (for this problem)**
  - split the phase space distribution $f \Rightarrow f_o + \delta f$
    - where full dynamics of f_0 is known analytically
    - evolve weights of macro-particles representing δf

Hu and Krommes, "Generalized weighting scheme for δf particle-simulation method," Phys. Plasmas **1**, p. 863 (1994).

    - one case already implemented in VORPAL

Xiang, Cary and Barnes, "Low-noise electromagnetic δf particle-in-cell simulation," Phys. Plasma **13**, 062111 (2006).